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The damage to hillside embankments in Sendai city during The 2011 off the Pacific Coast of Tohoku Earthquake

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Abstract

The 2011 off the Pacific Coast of Tohoku Earthquake resulted in severe damage to housing and housing lots. In particular, the hillside embankments for residential use surrounding the downtown of Sendai city suffered serious damage. Many hillside lands which had been damaged during the 1978 off Miyagi-Prefecture earthquake were subjected to further damage. Typical damaged hillside embankments in Sendai city were investigated and the causes of the damage were discussed in this paper. The main cause of the damage to housing was not the seismic motion but the ground displacement of the fill embankment. A comparison of the damage from the 2011 earthquake with that from the 1978 earthquake indicates that the countermeasures constructed after the 1978 earthquake performed well in that they prevented large landslide type failure; however, they were not successful in reducing the amount of damage to housing or housing lots due to ground displacements from cracks, differential settlement, and shallow slips. A classification of failure types of fill embankment is proposed to be of assistance in the choice of countermeasures.

Keywords: The 2011 off the Pacific Coast of Tohoku Earthquake; The great East Japan Earthquake; Hillside embankment; Sendai city; Housing damages; Valley filled embankment (IGC: C0/C7)

1. Introduction

At 2:46 P.M., March 11, 2011, a giant earthquake named "The 2011 off the Pacific Coast of Tohoku Earthquake" with a moment magnitude of 9.0 hit east Japan resulting in enormous loss of human life and social facilities. The earthquake and resulting damage is also called "the 2011 Great East Japan Earthquake". Hereinafter, we will use "the 2011 earthquake" for the sake of brevity. The causative fault of the 2011 earthquake is located in the Pacific Ocean off east Japan, the size of the causative mechanisms was 500 km in length and 200 km in width as shown in Fig. 1. The rupture area of this earthquake was so large and the rupture process during earthquake was so complicated that ground motions with different features were observed at different locations. Figs. 2 and 3 show a seismogram (in NS direction) and an associated velocity response spectrum observed at the surface of the hillside embankment in Sendai city (Kamiyama et al. (2011)). This data was observed by Small Titan (Kamiyama et al. (2001)). The strong motion was prolonged for more than 3 minutes and

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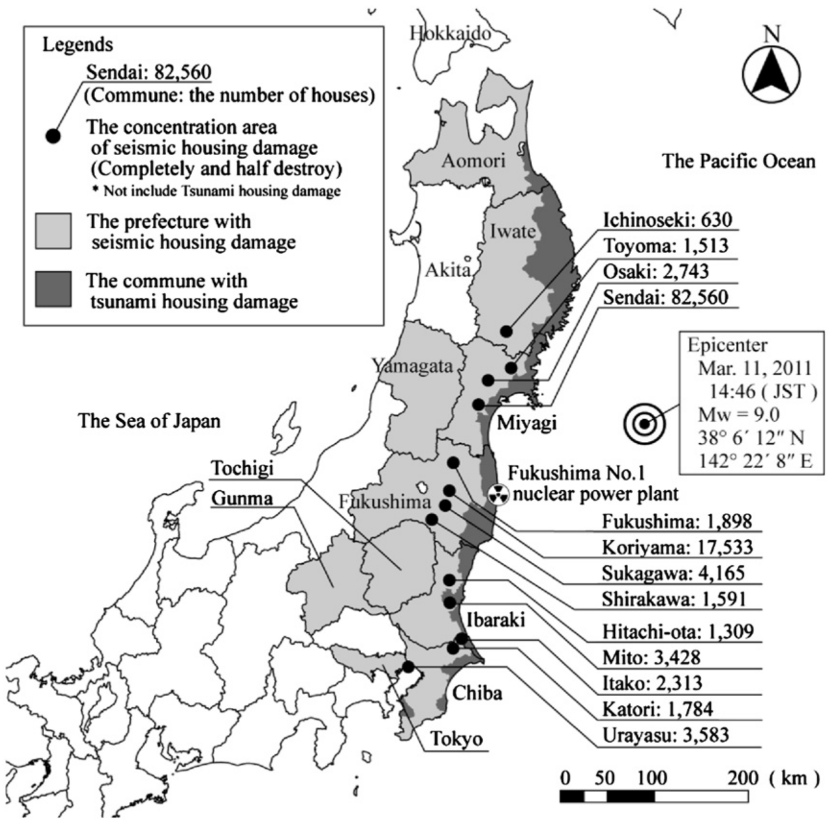

Fig. 1. Damaged area and the number of seismic housing damage in representative commune.

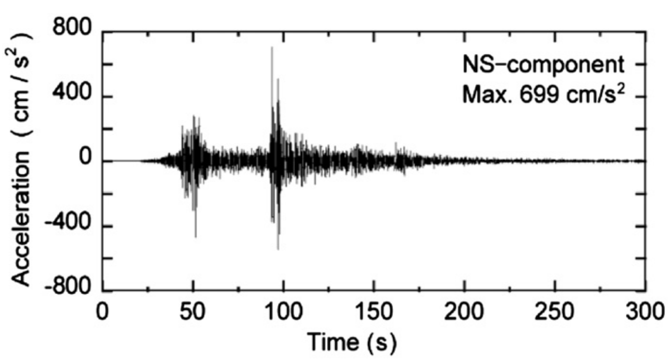

Fig. 2. Observed seismic acceleration record in Sendai city (Nankodai-Higashi elementary school) during the 2011 earthquake.

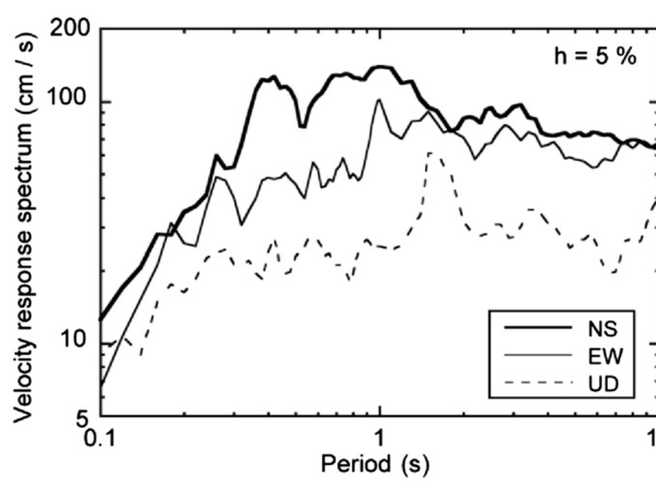

Fig. 3. Velocity response spectrum in Sendai city (Nankodai-Higashi elementary school) during the 2011 earthquake.

the maximum value of the seismogram in the NS direction was 699 cm/s^2. The velocity spectrum shows the predominant period to be around 1.0 s.

The damage to housing may be classified into tsunami-related damage, damage due to liquefaction of sandy ground on newly reclaimed land, and that caused by the instability of slopes and fill embankments developed for residential use. There was a huge number of damaged houses due to the tsunami, as shown in Fig. 1. The housing damages due to tsunami and due to liquefaction will be discussed elsewhere in this special issue. The focus of this paper is the damage done to housing lots on hillside embankments.

Emphasis is placed on the damage and failure of the housing lots on the hillside embankments in Sendai city, a city with a population in excess of one million, making it one of the largest cities in east Japan. The damage to hillside embankments in Shiroishi city 40 km south to Sendai city is also discussed in order to compare the damage due to the 2011 earthquake with that which occurred during the 1978 the off Miyagi prefecture earthquake.

First, we review the previous studies on the damages of hillside embankment for residential purposes during past earthquakes in Japan and summarize the main findings as a basis for understanding the damage incurred by the 2011 earthquake.

The damage to housing lots on hillside embankments in Sendai city and the causes of severe damage are discussed in detail with regard to four selected sites. Most of the hillside embankments for residential use which sustained damage from the 1978 earthquake were again seriously damaged during the 2011 earthquake despite the countermeasures such as groundwater wells and restraining piles, which were implemented to prevent damage from future hazards. An explanation of why damage occurred at the same hillside embankments will be discussed with an emphasis on whether the countermeasures performed well or not.

We close this paper with a tentative classification of the failure types of the hillside embankments during strong earthquakes based on previous studies and the present study in the hope that it may be useful as a guideline when selecting countermeasures.

2. Previous studies on the damage to hillside embankments during earthquakes in Japan

The susceptibility of hillside embankments to severe damage during strong earthquakes had been recognized from the 1978 off Miyagi prefecture earthquake with a magnitude of 7.4, which brought about damage to hillside embankments in several cities in Miyagi prefecture. Hillside embankments incurred severe damage in succeeding earthquakes, with the damage to housing due to ground collapse during the 1995 Great Hanshin Earthquake most worthy of note. After a detailed investigation of the damage, some fundamental and common features of the failure of hillside embankments and the associated damage to housings have been analyzed. We here review the main findings with regard to this hazard up to the present.

Asada (1978) carried out detailed investigations on the damage and failure of hillside embankments during the 1978 earthquake and found that valley filled embankments (which were created by filling valleys with soil cut from both sides of the original ground) and the boundary area between cut and fill were susceptible to severe housing damage due to the failure of embankments. He also investigated the relationship between the date of embankment construction and the ratio of completely destroyed and half destroyed housing and concluded that houses on the older hillside embankments tended to be more severely damaged.

Yanagisawa et al. (1994) examined the difference in damages between the cut area and fill area in hillside embankments during the 1993 off Kushiro earthquake, and they concluded that severe damage occurred both in the valley filled embankment sand in the partially filled embankment (which were created by constructing additional embankment to the existing land to enlarge housing lots). Fig. 4 shows the configurations of valley filled and partially filled embankments.

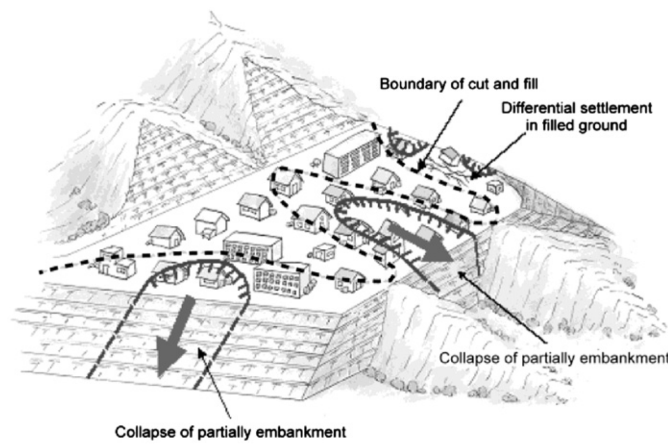

Fig. 4. Valley filled and partially filled embankments.

Okimura et al. (1999a) preformed detailed investigations on the damage to hillside embankments during the 1995 Great Hanshin earthquake and reported the following:

(1) Even when the slope angle of hillside embankment was gentle, those with loose soils and a shallow groundwater table were subjected to damage.
(2) Even when the slope angles were steep, hillside embankments with a deep groundwater table remained undamaged.
(3) Hillside embankments of 15 m or more in height were damaged seriously at the top of the slope, with the cause of the damage attributed to the amplified seismic motions due to the high embankment.

Okimura et al. (1999b) also classified the failure patterns of hillside embankments into 4 patterns by summarizing the previous findings on hillside embankment failure during strong earthquakes:

(1) The landslide type failure extending over the whole site appears in valley filled embankment, where slippage occurs along the boundary between the original ground and the embankment.
(2) Liquefaction results in the failure of sandy soils in an embankment with a shallow groundwater table, and the failure occurs along the slip surface or in the slip zone.
(3) A massive flow type failure of hillside embankment with gentle slope due to liquefaction yields a down-movement without a noticeable slip surface.
(4) The seismic motion of hillside embankments on weak ground is amplified and the seismically induced shear stresses exceed the strength of the soils in the embankments, which yields to slip failure.

Kamai and Shuzui (2002) reported in their book that valley filled embankments are susceptible to damage during earthquakes, and the shape of the cross section of the embankment had considerable effects on the damages. This result was obtained by applying the statistical analysis over the past damages.

Asada (2008) compared the SPT N values at the damaged sites during the 1978 earthquake in and around Sendai city in 1978, 1986, 1996 and found that a decrease in the N values was observed compared with those in previous surveys, which indicated the hillside embankments in and around Sendai city experienced some settlement with the lapse of time after the creation of lands.

By summarizing these studies, we are reminded of the importance of remembering the principal findings in investigations on the causes of seismically induced damages of hillside embankments:

(1) The classification of hillside embankments matters: valley filled embankments, partially filled embankments, and the boundary zone between fill and cut are most susceptible to serious damage;
(2) The date of the creation of hillside embankment affects the damage, the reason behind this may be attributed to the effectiveness of the regulations at the time the residential land was created and physical softening (aging effects).
(3) The state of soils in the hillside embankments is also an important factor: is it loose or dense?
(4) The water table in hillside embankments, which may be the result of the original topography and the properties of fill materials, play an important role particularly in the case of valley filled embankments.

These 4 factors play an important role in the failures of the hillside embankments, and should be kept in mind during investigations.

3. Damage to hillside embankments in Sendai City

3.1. Overview on damages of hillside embankment

The hillside embankments for residential use surrounding the downtown area of Sendai city were severely damaged during the 2011 earthquake. More than 4000 housing lots (corresponding to more than 7000 houses) were severely damaged and 63 sites with more than 10 damaged housing lots were counted (97 if counted in terms of house unit). Prompt reports just after the earthquake were made by Koseki et al. (2011) and Okimura et al. (submitted for publication) among others.

Table 1 shows the main results taken from the fundamental data on the 18 damaged sites in the detailed survey and investigation carried out by Sendai city after the 2011 earthquake (Sendai city (2011)). The locations of these 18 damaged sites are indicated in Fig. 5, and "no." in Table 1 corresponds to the number with a white circle in Fig. 5. One site (Midorigaoka 3 choume) was examined by Miyagi prefecture inspectors.

Guided by the essential factors affecting the damage of hillside embankment during earthquakes, we here summarize the main factors in the damaged hillside embankments in Sendai city.

(1) *The type of hillside embankment*: The damage in valley filled embankments was pronounced.
(2) *The soil type*: the soils in the damaged hills with high ratio of fine particles (less than 75 μm in diameters) used for filling, which experienced drainage problems. Proper drainage from the fill embankment was difficult. The soils with considerable fine contents also led to the rise-up of the water table in the hillside embankment.
(3) *The loose state of soils*: The state of soils may be identified by the N value from the standard penetration test (SPT for brevity in what follows). The SPT N values from the surface to the 5 m depth range from 0 to 5 in most sites, which clearly show the loose state of hillside embankments in Sendai city. The precise state of soils cannot be identified with the SPT N values only. More information about soils and detailed construction works on the fill embankment is required because no construction records have remained. In most cases the SPT N values are available to assess the state of filled soils and the original ground.
(4) *The thickness of fill*: the maximum depth of fill ranges from 6.0 m (Jingahara) to 26 m (Matsugaoka) depending on the original topography. The averaged depth of the fill varies from shallow (3.0 m at Aoyama 2 choume) to deep (18.0 m at Matsugaoka).
(5) *The level of the water table*: The water level of fill embankments is shallow in most cases, which may be attributed to the soil type with fine contents and to the bad performance of groundwater drainage works in fills.

The inappropriate state of filled soils is considered to play an important role on the failure pattern of the damaged hillside embankments. The failure patterns observed in each damaged site are listed in Table 1(see also Table 1 and Fig. 21).

Landslide type failure is expected to occur along the boundaries between the fill embankment and the original ground, which may be one of the causes of the damage of the embankment. Most of the damage can be classified as follows: ground displacement, which appears as shallow slips, open cracks, differential settlements due to the seismically induced densification of loose soils, a lack in the bearing capacity of the basement of retaining walls, or the liquefaction of sandy soils. It seems appropriate to note that the loose state of filled soils prevents large scale failure from occurring in many damaged sites, since massive failure associated with localized deformation such as slip surface requires the soils in embankments to have sufficient strength. There was no landslide failure type in the strict sense that such landslide should only occur within the original soft ground.

Table 1
Fundamental data on 18 damaged sites to which Sendai city carried out detailed survey and investigation after the 2011 earthquake.

No.	Name	Number of damaged housing lot (point)	Developed year (year)	Fill type (–)	Fill material (–)	The character based on the method of classification of geomaterials for engineering purposes (–)	Fine Fraction contect (%)	Classification of failure types (–)[a]	Ave. N-value (Dep. = 0–5 m) (–)	Fill thickness ($_{max}$./ave.) (m)	Ave. inclination of present ground surface (deg.)	Ave. inclination of old ground surface (deg.)	Groundwater table (G.L. (m))	Representative counter measure work (dimensionless)
1	Midorigaoka-2-choume	30	1955–1964	Valley filled	Clay contained sand and gravel	C-SG	76.3	(2)	0–4	8.0/5.0	9	11	−3 to −4	Prevention work, groundwater drainage work
2	Midorigaoka-3-choume	94	1961–1962	Valley filled	Sandy silt contained gravel	SM-G	47.7	(3)	0–8	21.0/10.0	8	7	−13 to −18	Prevention pile, groundwater drainage work
3	Midorigaoka-4-choume	107	1960–1965	Valley filled Partially filled	Silty sand	SM	34.0	(2)	0–3	7.0/5.0	12	8	−0.5 to −6	Retaining wall, prevention pile
4	Ootoya-machi	47	1955–1960	Valley filled	Gravelly clay contained sand	CG-S	61.2	(2) and (3)	0–2	7.0/3.0	11	8	−2 to −6	Prevention work, groundwater drainage work
5	Keiwa-machi	53	1955–1960	Valley filled	Fine sandy gravel	GFS	30.2	(2) and (3)	0–4	15.0/8.0	12–14	4	−1	Sliding control work, groundwater drainage work
6	Aoyama-1-choume	110	1963	Valley filled	Clayey sand contained gravel	SC-G	37.0	(2)	2–4	21.0/16.0	8	3	−1 to −15	Prevention work, recovery of retaining wall
7	Aoyama-2-choume	25	1963	Partially filled	Silty sand contained gravel	SM-G	33.4	(2)	0–5	8.0/3.0	9	9	−0.5 to −7.3	Anchor work, lateral bore hole
8	Matsugaoka Area	45	1960–1967	Valley filled	Clayey sand contained gravel	SC-G	36.7	(3) and (4)	3–4	26.0/18.0	7	8	−3	Reinforced soil wall
9	Oritate-5-choume	57	1965–1972	Valley filled	Sandy clay contained gravel	CS-G	59.7	(2) and (3)	1–2	12.0/7.0	8	8	−3.0 to −5.7	Steel pipe pile, culvert
10	Seikaen Area	20	1975–1978	Valley filled	Sandy silt contained gravel, Sand	SM-G	49.1	(2)	1–5	10.0/6.0	15	17	−1 to −10	Soil removal work, reinforced soil work
11	Takanohara-1-choume (North Area)	10	1989–1995	Valley filled	Finely sand contained gravel	SF-G	38.3	(2)	5	5.7/4.0	8	10	−1 to −3	Groundwater, drainage work
12	Takanohara-1-choume (South Area)	4	1989–1995	Valley filled	Sandy clay contained gravel	CS-G	52.3	(2)	2–4	8.7/6.0	11	13	−9	Soil removal work, counterweight fill work
13	Takanohara-2-choume Takanohara-3-choume	41	1989–1995	Northarn slope: Partially filled Eastern and western slope : valley filled	Sandy clay contained gravel, Sand	SC-G S	41.4	(3)	1–3	16.0/12.5	11	6	−6 to −9	Refilling
14	Nakayama-1-choume (Takimichi Area)	22	1965–1975	Valley filled	Silty sand	SM	49.4	3)	1–3	12.5/6.8	22	25	0 to −3.6	Recovery of retaining wall
15	Nakayama-5-choume	31	1965–1970	Valley filled	Silty sand	SM	36.2	(2) and (3)	0–4	15.0/12.0	8	5	−1 to −3	Prevention work, groundwater drainage work
16	Futabagaoka Area	54	1961–1965	Valley filled	Clayey sand contained gravel	SC-G	Unknown	(3) and (4)	3	16.0/5.0	11	12	−2.5	Steel pipe pile, culvert

17	Nankodai-6-choume	14	1962–1985	Valley filled	Silty sand contained gravel	SM-G	27.9	(3) and (4)	1–21 (ave=6.6)	14.0/10.0	8	5	−2 to −4	Sliding control work, groundwater drainage work
18	Jingahara Area	11	1975–1976	Valley filled	Silty sand contained gravel	SM-G	21.2	(3) and (4)	2–3	6.0/5.0	2	4	−2	Hardening work, open ditch and culvert

[a]Refer to Table 5 and Fig. 21.

4. Case studies on 4 hillside embankments

Four damaged hillside embankments, which experiences damage for different reasons, were selected from the 18 damaged sites listed in Table 1. We discuss the failure type and the mechanisms yielding to severe damage for each site.

4.1. Midorigaoka 3 choume (failure type: landslide type failure and ground displacements)

Midorigaoka 3 choume is a hillside embankment for residential use which suffered severe damage during the 2011 earthquake. It is locate 3 km south-west of the JR Sendai station (numbered as 2 in Fig. 5; "choume" means a numbered subdivision of an area). The residential land had previously suffered enormous damage due to landslide type failure during the 1978 earthquake, which apparently occurred along the boundary between the fill embankment and the original ground. After the 1978 earthquake, 427 restraining piles 32 cm in diameter and 16–25 m in length were placed into the original ground in 5 rows in a zigzag fashion almost vertical to the slope movement and two groundwater drainage wells were constructed. The arrangements are shown in Fig. 6 (see also Photo 1). The housing lots in Midorigaoka 3 choume suffered serious damage again during the 2011 earthquake despite the countermeasures taken after the 1978 earthquake.

Figs. 7 and 8 show the plan and cross-sectional views of the damaged areas, the outline of the damage, and the arrangements of the piles and wells. There are two relatively narrow valley filled embankments in the land. The fill materials are composed of sandy soil with gravel and cohesive soil with gravel. The cohesive soil used for the creation of the hillside embankment is rather poor, since they contain large amounts of fine particles. No clear transition between them was observed: instead they were filled in a mixed way. The range of severe ground displacements (shallow slips and subsidence) and the distribution of surface cracks are shown in Fig. 7. The movement and the angles of inclination at the top of restraining piles are also shown in Fig. 7. Since sand boils were observed by the residents, liquefaction induced displacement is also supposed to have had an effects on the damage. The drainage from the embankment using the two groundwater drainage wells apparently was working well, with the lower level of the water table kept at -13 m to -15 m from the ground surface. The restraining piles which were fractured during the 2011 earthquake were also effective to prevent a landslide type of movement from occurring. Both countermeasures appear to have performed well during the 2011 earthquake; nevertheless, the damage incurred to houses on the housing lots on the valley filled embankment was almost equivalent to the damage during the 1978 earthquake. The severity of the damage during the 2011 earthquake to Midorigaoka 3 choume, which had been reinforced with wells and piles,

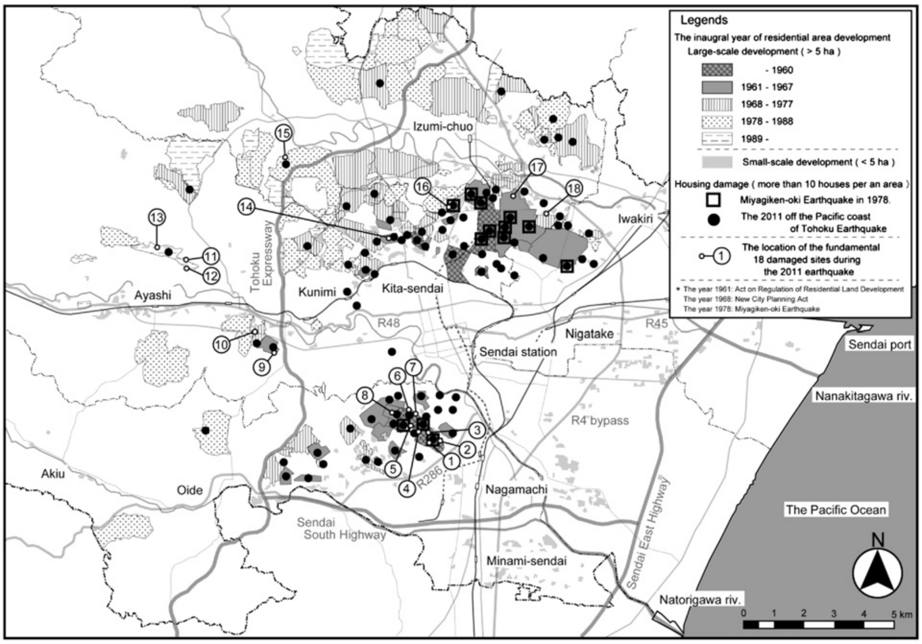

Fig. 5. Developed era of residential area, and damaged area in the 1978 earthquake and the 2011 earthquake.

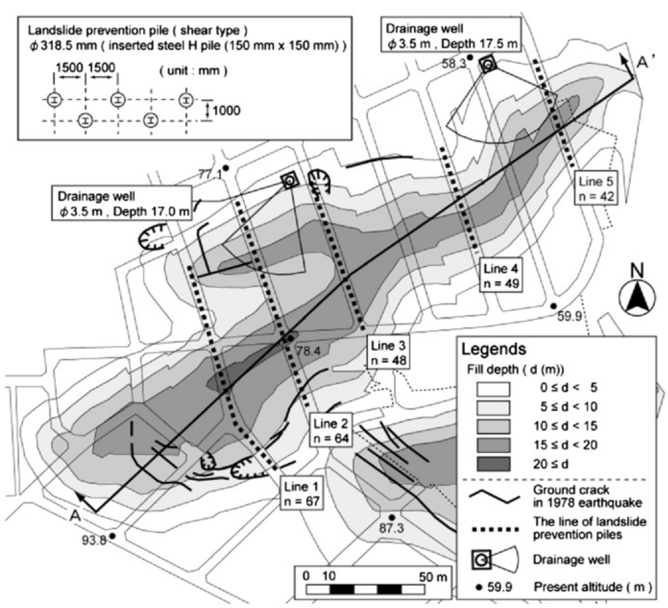

Fig. 6. Plan view on ground damages and countermeasures of Midorigaoka-3-choume in 1978.

suggests that due attention should be paid to the state of the fill materials. The effects of the loose state of fill materials on the damages of housings and housing lots during seismic motions will be discussed in the next chapter.

The main causes leading to the severe damage in Midorigaoka 3 choume may be summarized as follows: (1) it was a valley filled embankment; (2) there was a higher saturation of fill materials partly due to the considerable amount of fine contents as well as due to the original topography gathering rainfalls; (3) the slope angle of the ground surface was relatively steep (8° on average) facilitating the down-movement of slopes in the case of liquefied soils.

Photo 1. Exposed Piles after the 2011 earthquake (Midorigaoka-3-choume).

4.2. Oritate 5 choume (failure type: landslide type failure in fill and ground displacements)

Oritate residential land is located (numbered as 9 in Fig. 5) 8 km west of downtown of Sendai city. Ground for housing was started to be created in 1965 and completed in 1972. No damage occurred at this site during the 1978 earthquake. A lot of housing lots and houses suffered serious damages during the 2011 earthquake in this site on a valley filled embankment. Figs. 9 and 10 show the plan and cross section views of this site. The angle of inclination of hillside embankment was from 6° to 8°. The fill material was composed of cohesive soils with gravels; the original ground was composed of silt rock and gravel rock.

The survey after the 2011 earthquake showed that the water table was shallow at just −3 m below the surface, and that the SPT N values were from 0 to 3, which indicates that the filled materials were quite loose. A comparison of the two satellite photographs of before and after the 2011 earthquake indicates remarkable displacements: 0.6 m at the crest, 2.5 m at the center, and 2.0 m at the tip of damaged area. The displacement measured by in-situ strain measures which were installed after the earthquake have been less than 10 mm, which indicates that succeeding displacement after the earthquake did not occur.

Photo 2 shows the displacements at the tip of the damaged area. The clearly damaged areas and undamaged areas are clearly distinguished by the major cracks crossing the road, the near side (supposed to be "cut" part of the original ground) from the cracks appears to show no damage, while the far side from the crack was severely damaged. The fill embankment was severely damaged, the bulging of pavements showing the occurrence of compressive buckling, the walls set up on the top of poorly created retaining walls slid and tilted toward to the road amounting to 1.0 m. Photo 3 shows the view taken from the crest to the center of the damaged valley fill embankment. Many cracks broke the road into small pieces. These cracks suggest that a valley filled with cohesive soils was displaced severely due to seismic motions, in particular at the shallow part of the embankment. The depth of ground displacements in the fill embankment was estimated to be shallow; the elastic wave exploration indicated that the depth of displacement was about −5.0 m at the center and −7.0 m at the tip of the damaged area.

It is worthwhile noting from these observations that the severe damage to housing and housing lots at this site can be primarily attributed to the severe ground displacement of weak fill materials near the surface; the damage was the consequences\ of shallow slip movements, many cracks, and differential settlements. Since a large landslide type failure is also expected at this site, attention should also be

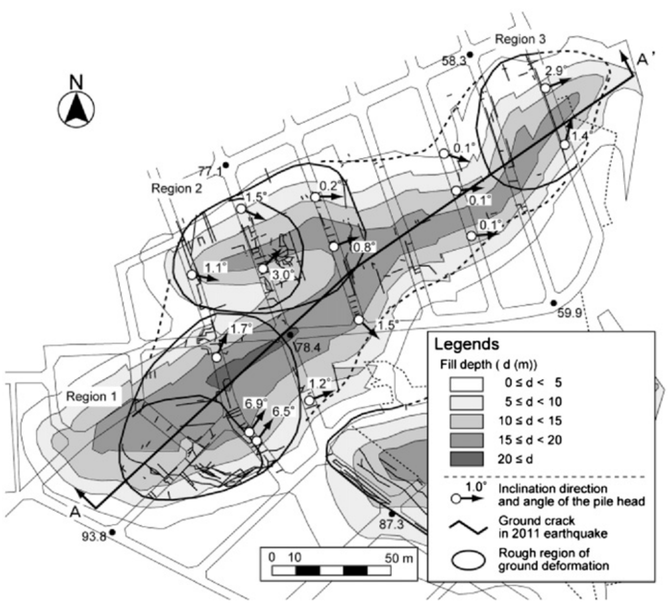

Fig. 7. Plan view on ground damages of Midorigaoka-3-choume in 2011.

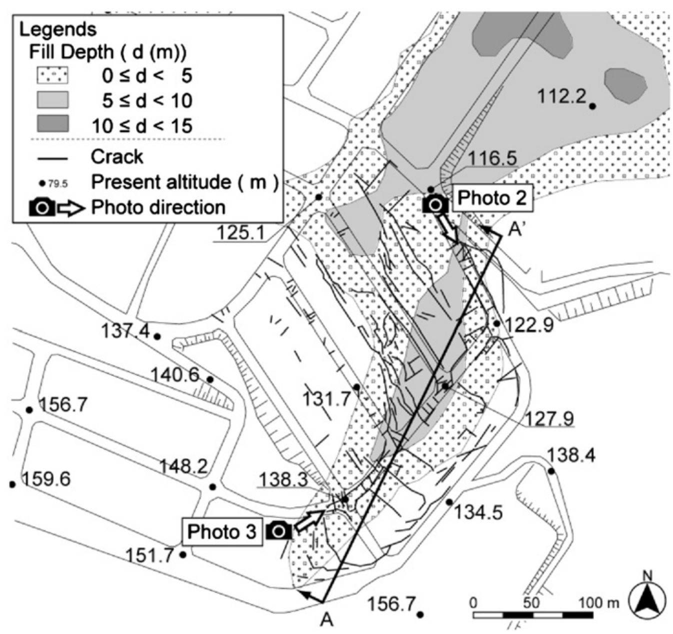

Fig. 9. Plan view of Oritate-5-choume.

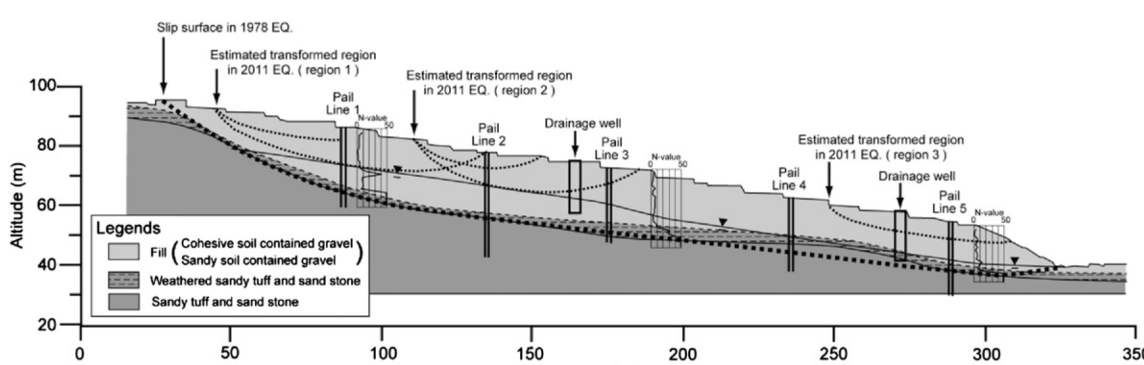

Fig. 8. Cross section view of Midorigaoka-3-choume along A–A′ in Fig. 7.

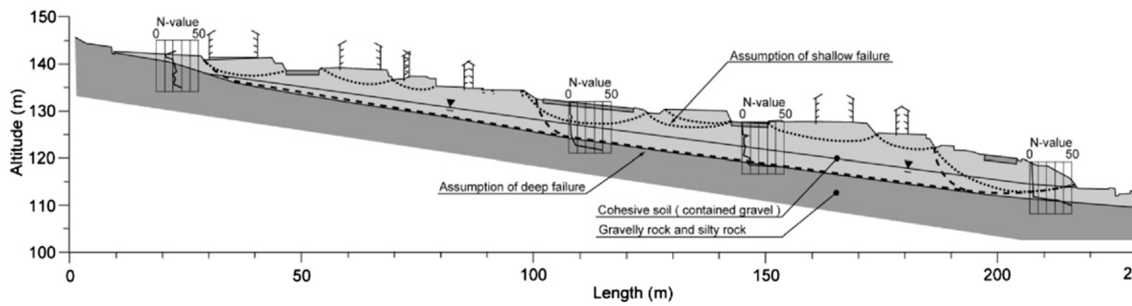

Fig. 10. Cross section view of Oritate-5-choue along A–A′in Fig. 9.

Photo 2. Ground displacement at tip of damaged area (Oritate-5-choume).

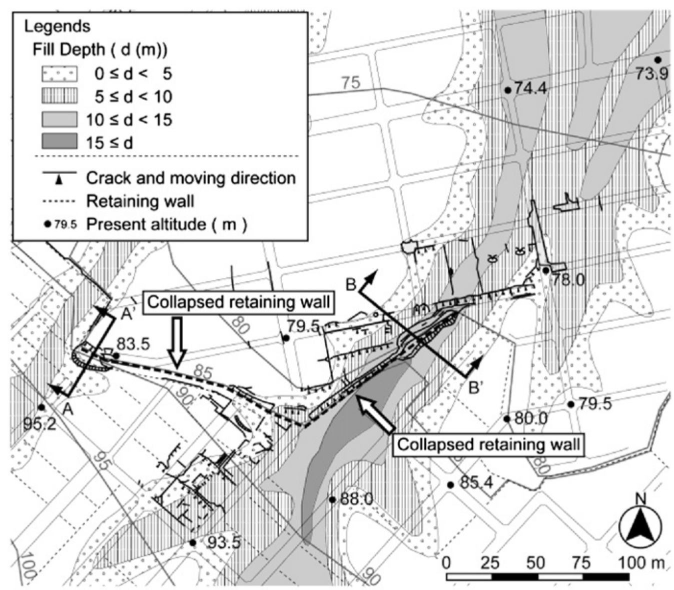

Fig. 11. Plan view of Takimichi area.

Photo 3. View from the crest of damaged valley fill embankment (Oritate-5-choume).

paid to the selection of countermeasures which could prevent a large landslide type failure event from occurring.

The causes of severe damages at this site may be summarized as follows: (1) it is a valley filled embankment with a shallow water tables; (2) the filled material is composed of cohesive soils; and (3) the soils had a lower SPT *N* value, indicating that they were loose.

4.3. Nakayama 1 choume and Takimichi (failure type: failure of the retaining wall)

Nakayama 1 choume and Takimichi are residential land north of downtown of Sendai city, located at the boundary between the downtown and the outlying suburbs (numbered as 14 in Fig. 5). The creation of the hillside embankment for residential use started in 1965 and was completed in 1975. At this site, two collapsed retaining walls were crossed at an angle of 135° with one extending to the west direction and the other to the northeast direction (see Fig. 11). The residential land is slightly inclined downward from southwest to northeast, and the valley filled embankment was created along the same direction. Large retaining walls were constructed for the convenience of construction of the residential land: they are 5–9 m in height and are inclined 50–60° to the horizontal ground. The fill depths of embankments were as deep as 17 m at the maximum depth on the east side. No noticeable failure was noted as a result of the 1978 earthquake, but during the 2011 earthquake, the retaining walls failed with associated damage to the backfill occurred in the west direction. The failure of retaining walls in the northeast direction was associated with the circular slip movement in the fill embankment.

Fig. 11 shows the location of the damaged retaining walls, associated cracks, and the fill depth. With regard to the location of the fill and cut boundary with relation to the cracks, a large number of cracks appeared on the fill part, in particular on the fill part adjacent to the boundary between fill and cut.

The damaged retaining wall to the west was set up on the cut side, as seen in the cross section view shown in Fig. 12. The retaining wall was 8.0 m and constructed in 2 stairs, with a foundation composed of weathered gravel rock. The backfill materials were composed of cohesive soil with gravel with SPT *N* values were from 3 to 8. The groundwater table at the onset of the 2011 earthquake was estimated to be shallow. There was no apparent ground displacement on the lower ground surface adjacent to the retaining walls, with ground displacement occurring only in the backfill. The complete failure of the retaining wall set up on the cut part in the west direction can probably be attributed to the inertia force due to the seismic motion; however the use of cohesive soils as backfills and the shallow groundwater table played certainly an important role in the failure (see Photo 4).

Fig. 13 shows the cross section view along the line B–B′ (which is located in the northeast direction). The backfill materials were composed of cohesive soils containing gravel, with SPT *N*-values from 0 to 7. The bulging of the lower ground surface was evidence of the occurrence of circular slip movement (see Photo 5). The failure of the retaining walls on the northeast direction appeared to be associated with the failure of the ground. Around the damaged retaining walls, there were several indications of ground displacement, such as the bulging of retaining wall, horizontal slips and the bulging of the base foundations.

Even though the causes of the failures at this site appear to be similar, the failure patterns of the retaining walls were completely different, and depended on the bearing capacity of the retaining wall. The common causes behind the failure of the retaining walls in both directions may be summarized as follows: (1) the poor structure of retaining walls (too high and too steep); (2) the cohesive soils; (3)

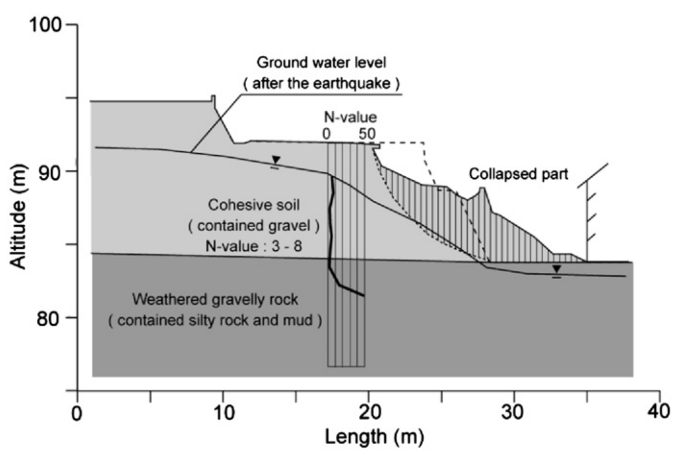

Fig. 12. Cross section view of Takimichi area along A–A′ in Fig. 11.

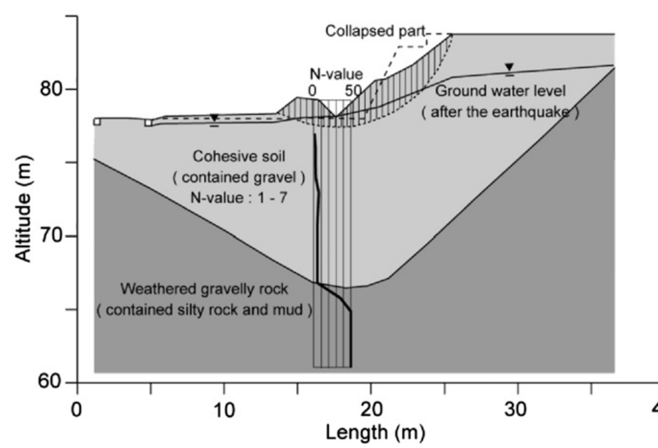

Fig. 13. Cross section view of Takimichi area along B–B′in Fig. 11.

Photo 4. Failure of retaining wall in the west direction (Takimichi).

Photo 5. Circular slip movement in the northeast direction (Takimichi).

the looseness of the backfill materials; and (4) a shallow groundwater table. The combination of these factors resulted in larger earth and water pressures, which led to the failure of the retaining walls.

4.4. Takanohara 2,3 choume (failure type: slope failure at the top of fill embankment)

Takanohara residential land is 10 km west of downtown of Sendai city (numbered as 13 in Fig. 5). The land construction to create the embankment was started in 1989 and completed in 1995. This residential land is the newest among the hillside embankments which were damaged substantially during the 2011 earthquake. The damage in this site was classified as slope failure at the tip of the embankment.

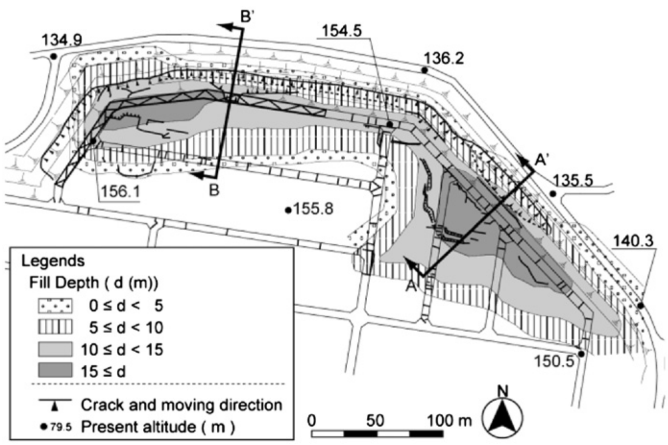

Fig. 14. Plan view of Takanohara-2-choume.

Fig. 14 shows a plan view of this site, with the location of damages and the fill depth also shown. The residential land was created by cutting the central part of the hills and filling the surrounding lower area. This site has irregularly distributed valley filled embankments and partially filled embankments at the outer part of the land, which reflects the original topography. The east and west sides of the damaged area were a valley filled and a partially filled embankments respectively, with a maximum fill depth of 17 m. Many open cracks due to tension force appeared along the roads located at the top of slope surrounding the lands. Displacement due to bulging appeared mid-slope. Field observation indicated that the top of the slope was shaken severely by the strong seismic motion.

Fig. 15 shows the cross section of the damaged embankment on the east side (along the A–A′ line in Fig. 14). A fill embankment amounting to 17 m in height was created on a bedrock of sand stone or silt stone. The fill materials were composed of gravel, sand, and clay, and different soils were filled in an irregular way. The SPT N values showed a wide scatter from 1 to 20. The groundwater tables were deep overall and that at the mid-part of the damaged slope was kept at -7.0 m. In this cross-section, shallow displacement appeared on the mid-slope of the embankment and bulging occurred on the bottom. Many cracks also appeared on the flat part of the residential land; however, no interaction with the displacements of the slopes was supposed. Fig. 16 shows the cross section of the damage at the west side of the land. The displacement which appeared from the mid-part to the top of the slopes suggests slip type movement, and bulging occurred at the bottom. By comparing the two sections shown in Figs. 15

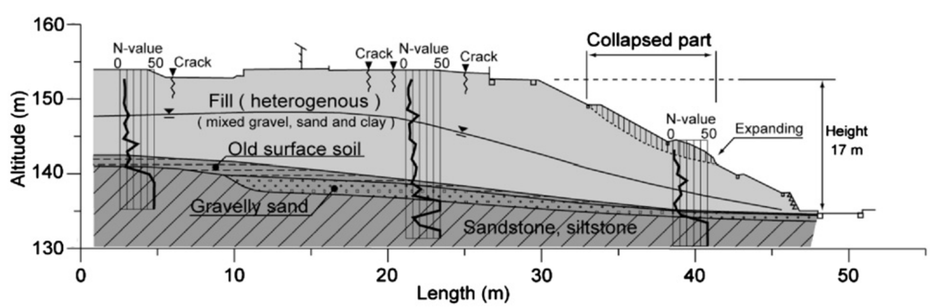

Fig. 15. Cross section view of Takanohara-2choume along A–A′ in Fig. 14.

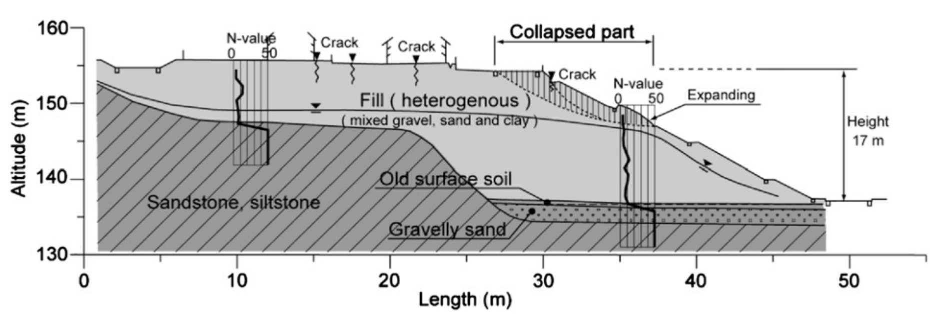

Fig. 16. Cross section view of Takanohara-2choume along B–B′ in Fig. 14.

and 16, we may note that the water table along B–B′ was remarkably shallow, with the bottom part just −1.0 below the surface; while the water level at the A–A′ section was deep. The difference in the groundwater table may have partly attributed to the different soil properties.

Considering the above observations, the primary cause of the cracks at the top of slopes may be the height of the embankment, which makes the seismic motion at the top of the slope more severe due to amplification. The assumption of the predominant role played by amplified seismic motion in the damage at this site may be partly justified by the fact that along B–B′ line, slope failure occurred from the top to the mid parts of the embankment with deep water tables rather than at the bottom part where the water table was shallow.

5. Comparison of the 2011 earthquake with the 1978 earthquake: the effectiveness of countermeasures

Countermeasures were taken in the most severely damaged residential land after the 1978 earthquake; however, most of these areas suffered damage again during the 2011 earthquake. In this chapter, attention will be paid to the residential land subjected to damage twice due to both earthquakes, where substantial countermeasures were taken in two cases, while no countermeasures were taken in one case. Through these comparisons, we discuss the effectiveness of the countermeasures put into place after the 1978 earthquake and also discuss the effects of the degradation of hill embankment due to the elapse of time after their creation.

5.1. Midorigaoka-3 choume (the countermeasures were piles and groundwater drainage wells)

We first discuss the case of Midorigaoka 3 choume where restraining piles and a groundwater drainage well were constructed after the 1978 earthquake as countermeasures. The causes of the damage to this land have already been discussed in a previous chapter: we here discuss the same site with an emphasis on the effectiveness of the countermeasures. The landslide type movement along the boundary between the fill and the original ground resulted in extensive damage to houses and housing lots. After the 1978 earthquake, 426 restraining piles in 5 stairs and two wells for groundwater drainage were constructed, which showed a good performance during the 2011 earthquake in the sense that they prevented a large landslide from occurring. However, many modes of displacement occurred in the ground with shallow depths (amounting to 4 m or less). The displacements may be attributed to the nature of soft ground which was subjected to seismically induced cyclic loadings. Ground displacements such as open cracks and differential settlement were observed between the parallel rows of piles. The shear deformation of the fill materials adjacent to the piles was constrained, and the accumulation of shear deformation led to the compressive bulging of the ground near the row of piles. The ground displacements which occurred in the housing lots resulted in severe damage to the houses.

5.2. Midorigaoka residential land (Kotobukiyama) in Shiroishi city (the countermeasures were wells and refill with a gentle slope)

We here discuss the case of Midorigaoka residential land (previously called as "Kotobukiyama" at the time of the 1978 earthquake), where two groundwater drainage wells were set up as the countermeasure after the 1978 earthquake.

This Midorigaoka land in Shiroishi city is located 35 km southeast of Sendai city. The creation of fill embankment for residential use started in 1972 and was completed in 1978. No houses had been built on the land at the time of the 1978 earthquake. The bedrock of the land was tuff (hard volcanic rock composed of compacted ash). Crushed rock was used as fill materials. The water table was shallow and the water content of the fill embankment was high because of heavy rain prior to the earthquake. The SPT N values of the fill embankment before the 1978 were reported to be between 5 and 13. The valley filled embankment was severely damaged and flowed downward about 100 m, with a run-off volume estimated at 80,000 m^3 (Figs. 17 and 18).

Fig. 18 shows the cross sections of the damaged fill embankment after the 1978 earthquake along the line A–A′ in Fig. 17. The fill depth amounted to 25 m at the top of the slope and the maximum slope angle was 23°. The shallow groundwater table was partly due to filling over a pond. After the collapse as the result of the 1978 earthquake, the fill embankment was re-filled with a slope angle of 10° with a drainage system consisting of a stone filled net and two water collection wells constructed at the

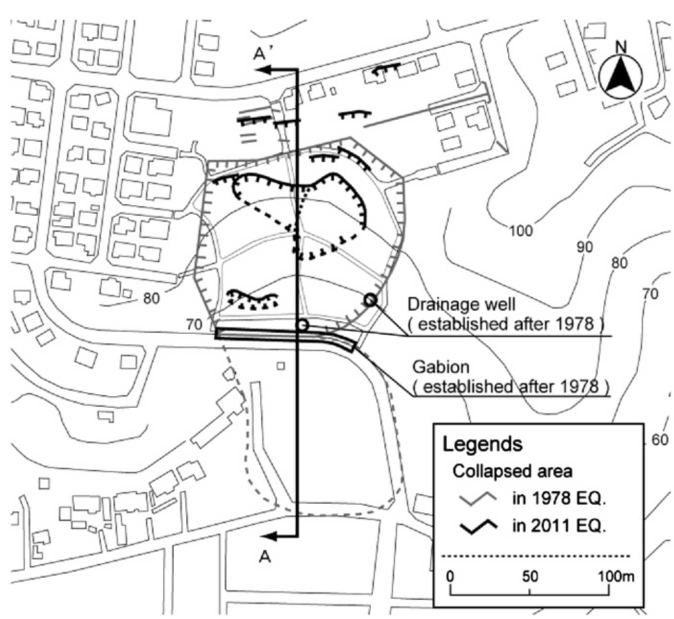

Fig. 17. Plan view of Midorigaoka residential land (Kotobukiyama).

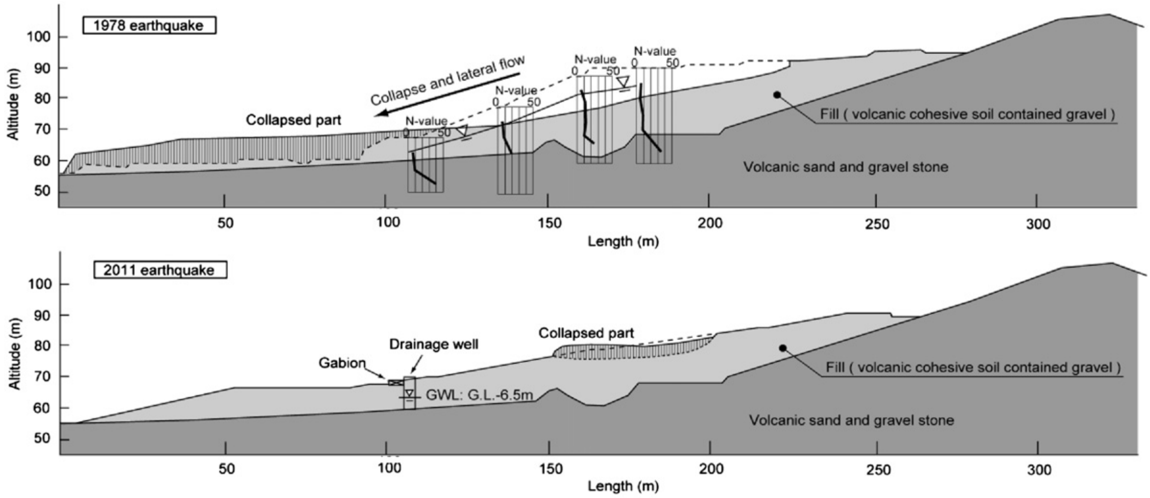

Fig. 18. Comparison of cross section views between the 1978 earthquake and the 2011 earthquake along A–A′ in Fig. 17.

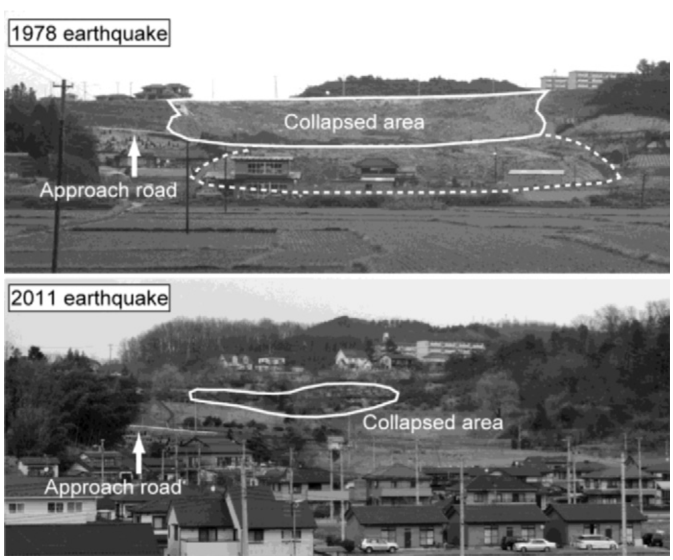

Photo 6. Comparison of collapsed area after the 1978 earthquake with that after the 2011 earthquake (Midorigaoka residential land (Kotobukiyama)).

toe of the slope in order to drain groundwater from the embankment. During the 2011 earthquake, many small slip failures with a shallow depth of at most 4 m occurred from the top to the mid-part of the embankment where the slope angle was relatively steep and no groundwater drainage system had been put in place, however, no remarkable ground displacement was observed near the toe part of the embankment, where the slope angle was gentle (about 10°) and the drainage worked well. The water table at the toe part remained at -6.5 m from the ground surface. Photo 6 shows the configuration of the collapsed fill embankment after the two strong earthquakes. A much smaller area collapsed area during the 2011 earthquake than during the 1978 earthquake.

Observations indicate that the groundwater drainage wells and stone filled net and the reconstruction of the slopes with an angle of at most 10°were successful to prevent large landslide from occurring. In the Midorigaoka land, most of the fill embankment was used as a park and a garden and there were no private houses in the area which had been seriously damaged during the 1978 earthquake. If the re-filled embankment had been used for residential use, devastating damage to housing would have inevitably occurred, considering the extensive slips, open cracks and the differential settlement from the top to the mid-part of the slope. It should be noted that 5 houses at the top of the slopes with a steeper slope angle (about 20°) were severely damaged, where no damage had occurred during the 1978. The countermeasures put into place to prevent a large landslide type of collapse were not sufficient to reduce housing damage.

5.3. Nankodai residential land (no countermeasures after the 1978 earthquake)

The Nankodai residential land was damaged severely due to both earthquakes. It is important to note that no countermeasures were taken after the 1978 earthquake, since no large landslide type movement occurred during that quake. The Nankodai residential land is 4 km north-east of downtown Sendai city. The creation of the fill embankment for residential use started in 1962. The ground surface of this site appears to be a gentle hill. However, the distribution of the valley fill embankment is very complicated, reflecting the original topography (see Fig. 19). The houses and housing lots on this site suffered damage during the 1978 earthquake, and were again subjected to severe damage during the 2011 earthquake.

The distribution of completely and half destroyed houses is indicated by black circles and black triangles for the 2011 earthquake and by white dots and white triangles for the 1978 earthquake in Fig. 19. In this figure, the horizontal axis is divided into 6 sections from A to F and the vertical axis is divided into 9 sections from 1 to 9 to indicate the location of the damage. At this site, there are three main valleys. These valleys will be

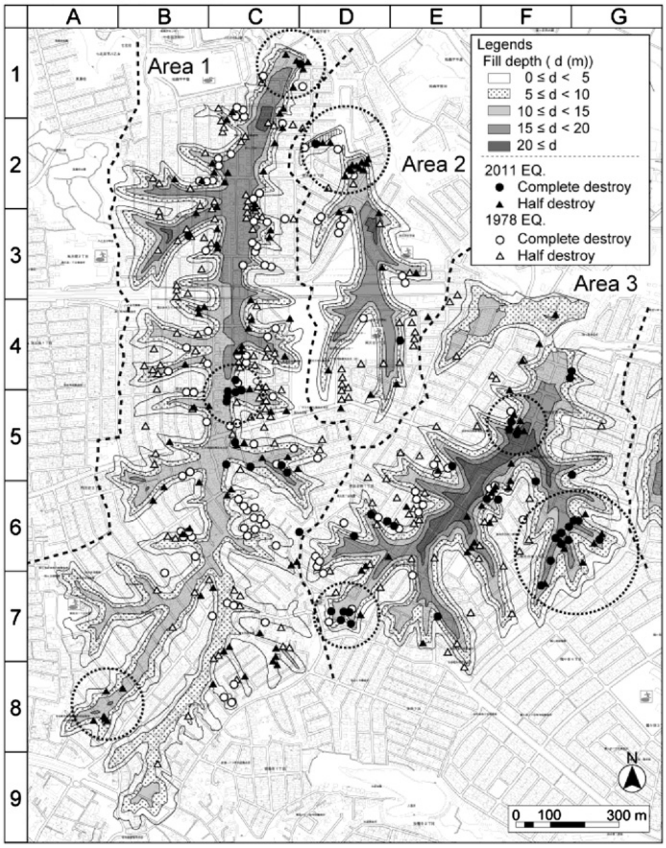

Fig. 19. Comparison of seismic house damages during the 1978 earthquake with those during the 2011 earthquake (Nankodai area). The Cut-Fill map (background map) was created by Fukken Technical Consultant (2010).

referred as Areas 1–3 from left to right for convenience. The housing damage was more severe on the fill part and along the boundary between fill and cut, and little damage occurred on cut part. It should be noted that a comparison of the damage incurred by the two earthquakes at this site indicates an increase in housing damage due to the slope failure of the fill embankment corresponding to the end of the valley in the original topography in C-1 and D-2. It should also be noted that houses at the uppermost section of the valley were more severely damaged during the 2011 earthquake, located at A-8, D-7, F-6 and G-6. On the other hand, the amount of damage to houses appeared to decrease in the branch valley. In Area 3 the damage to housing on the fill embankment with a maximum fill depth appears to increase, as is the case in F-5, which is the opposite tendency to that in B-4 and C-6.

The surveys on this site remain at a first stage and further surveys and research is required to identify the mechanisms behind the damage to the residential land with a gentle slope, in which landslide type failure did not occur.

5.4. A brief summary of the comparisons of damage

It may be said from the comparisons made in the above 3 cases that the countermeasures taken after the 1978 earthquake, such as the use of restraining piles and groundwater drainage wells, were effective in the reduction of seismic damages, and were particularly effective in the prevention of landslide type movement in hill embankments along the boundary between the fill and the original ground. The effectiveness of these countermeasures in the reduction of damages to houses and housing lots is questionable, at best.

In order to reduce housing damage, shallow displacements, like cracks, slips, and differential settlements, should be kept as small as possible. To ensure this, other types of countermeasures, such as soil improvements, the use of reinforced embankments and so on are preferred.

The groundwater drainage well was found to be efficient in the reduction of damage to housing lots, which suggest the positive use of groundwater drainage works in the restoration of damaged fill embankments. The use of groundwater drainage is considered effective for use when the fill materials are characterized by high permeability.

In most cases in Sendai city, soils containing fine particles like silts and clays are used as fill materials. The use of a groundwater drainage system for soils with low permeability is questionable for the following two reasons: (1) When soils with low permeability are used, the efficiency of the groundwater drainage is certainly reduced compared to those with high permeability. (2) When soils with fine particles are used as fill materials, the degree of compaction is poor, which leads to loose soil; and the subsidence of housing lots would be a concern if a groundwater drainage system was used as a countermeasure.

In spite of these points, it is suggested that a groundwater drainage system is the preferred countermeasure for damaged hill embankments. This suggestion is partly supported by the observations on the above two damaged fill embankment (Midorigaoka 3 choume in Sendai city and Midorigaoka (Kotobukiyama) in Shiroishi city) where few if any housing lots and slopes were damaged in the areas influenced by groundwater drainage wells. Groundwater drainage systems in damaged hill embankments is believed to have a positive effect on the hydraulic conditions leading to a deeper water table and in ensuring a higher strength of soils by unsaturation.

6. Some critical discussions on the damage of housings on fill embankment

We here discuss the followings problems with an emphasis on the case of Sendai city. What are the most critical factors contributing to the damage of hillside embankment land for residential use? What are the most critical factors in the damage to relatively new fill embankments? Finally, what is the main mechanism leading to the damages of houses?

6.1. What is the most critical factor on the damages of hillside embankment?

In the past strong earthquakes in Japan and the 2011 earthquake, hillside embankments for residential use have been damaged seriously. The causes of the damage may be attributed to the following: (1) the fill materials are composed of soils containing a high percentage of fine particles, (2) a shallow water table which destabilizes the hillside embankment, (3) the loose state of fill materials which may be due to poor compaction during the construction stages or due to the degradation of ground over the course of time, and (4) poor treatment of the boundary between the fill and the original ground which makes a landslide type failure possible.

In the case of the 2011 earthquake, generally speaking, the most important role in the damage to hillside embankments was played by the soil properties of the soils with fine particles used for fill materials. The soil properties determine the looseness of the ground, the depth (shallowness) of the water table, and the degradation of soils as time elapses. Detailed surveys should be done, the type of construction work should be considered carefully, and groundwater drainage should be properly established when soils containing fine particles must be used as a fill material.

In the case of public geo-structures such as fill-type dams and river embankments, continuous survey and maintenance should be carried out by the agencies responsible for those structures; however, neither survey nor maintenance is performed for residential land for private housing. It is strongly recommended that appropriate countermeasures are taken with existing residential land prior to a strong earthquake in accordance with the "Act of Promotion of Earthquake Resistant Residential Land", which is believed to have enormous benefits to the residents.

6.2. What were the most critical factors in the damage to relatively new fill embankments?

We here discuss the critical factors affecting the damage to housing on relatively new fill embankments. Recently developed land, if it is regulated by the law, is in better condition than older land, thanks to the high performance of construction works, well compacted fill materials, and the lower water table due to the groundwater drainage works, all of which may reduce the seismic damage. The Takanohara 2, 3 choume case mentioned in the previous chapter is an example of recently developed land, where the start of land creation was in 1989.

The SPT N value at the surface was relatively weak from 1 to 5 after the 2011 earthquake, which may have resulted from the fact that the fill materials were cohesive soils. The groundwater level was deep. The slope surrounding the residential land collapsed partly during the 2011 earthquake. One of the reasons of this collapse may have been that the fill is deep, with a maximum depth of 17 m.

Previous studies have shown that the seismic motion on fill with considerable height and on the top of the slope of fill embankment is amplified. As an example, Mori et al. (2010) reported that on a valley filled embankment with a depth of fill 23 m in Sendai city, where the maximum acceleration was 160 cm/s^2 at the top of the slope, and 96 cm/s^2 at the base of the slope during the 2008 Iwate-Miyagi Nairiku Earthquake.

It is thus understood that newly developed land with improved geotechnical conditions are likely to suffer damage due to amplified seismic motion, in particular, at the top of the slope of the fill embankment. It is strongly recommended that building housing on the top of slope of high hill embankments should be avoided, with the land at the top used instead for public parks and/or round roads.

6.3. What is the main mechanism leading to the damage of houses?

As has been discussed in the preceding chapters, the damage to houses is strongly affected by the displacement at the ground surface of fill embankment rather than landslide type failure. In this section, we present a tentative study, indicating the most important mechanism among the types of displacements at the ground surface.

To this end, Nankodai residential land was selected as the site of field investigations, which extends 2 km in the north–south axis and 1.5 km in west–east axis. The damage state of 6450 houses within Nankodai residential land was investigated from April 8 to 26, 2011.

Fig. 20 shows the distribution of damaged houses and ground cracks. Table 2 shows the number of damaged houses, divided into three categories: completely destroyed, half destroyed, and partially destroyed. The completely and half destroyed house are not suitable for residence. However, it is possible to reside in partially destroyed

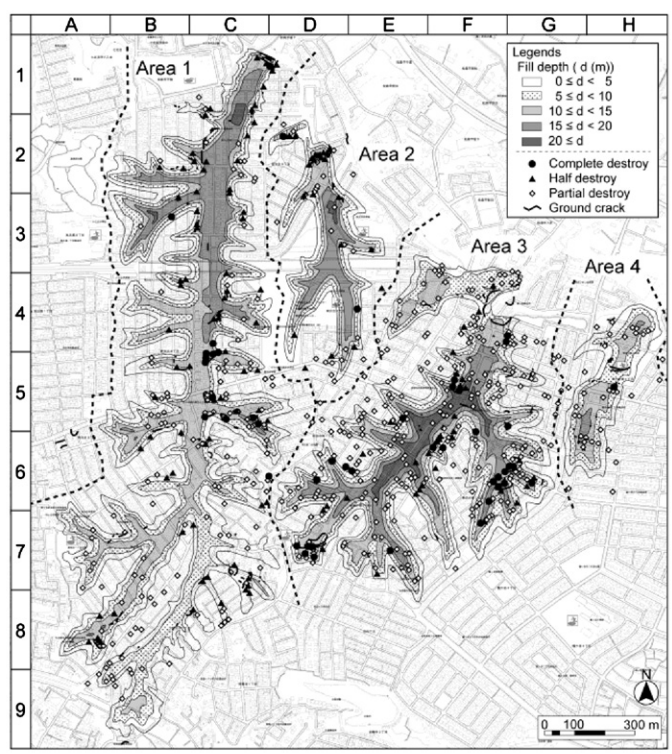

Fig. 20. Distribution of damaged houses in Nankodai area during the 2011 earthquake.

Table 2
Number of damage in Nankodai area.

Number of damage (Areas 1–4)									
Division	Area (km^2)	Area ratio (%)	Total houses (houses)	Comp. destroy (Houses)	Half destroy (houses)	Partial destroy (houses)	Road hair crack (point)	Gorund crack (point)	fence (Point)
Filled part	1.112	46.0	3206	34	67	264	1189	104	144
Boundary part	0.438	18.1	1110	13	63	96	373	30	62
Cut part	0.865	35.8	2224	1	5	73	169	6	33
Total	2.415	100.0	6540	48	133	433	1731	140	239

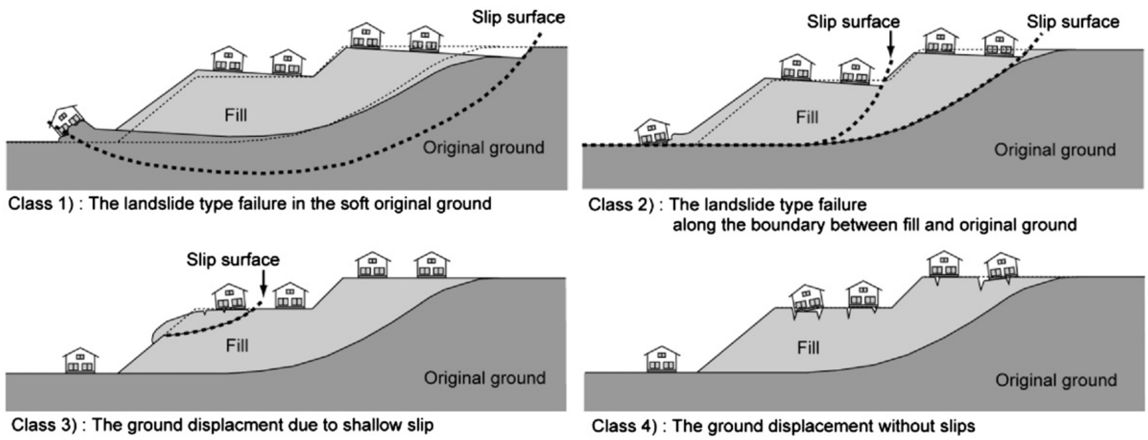

Fig. 21. Schematic figures for the tentative classification of failure type discussed in Table 5.

Table 3
Ratio of damaged houses being normalized to cut part in Nankodai area.

The normalized ratio to cutt part (Areas 1–4)							
Division	House density (–)	Comp. destroy (–)	Half destroy (–)	Partial destroy (–)	Road hair crack (–)	Gorund crack (–)	Fence (–)
Filled part	1.12	26.46	10.43	2.81	5.48	13.49	3.40
Boundary part	0.99	25.68	24.50	2.60	4.36	9.88	3.71
Cut part	1.00	1.00	1.00	1.00	1.00	1.00	1.00

houses, but with some difficulties. The residential area was divided into 3 categories: fill, boundary (between cut and fill), and cut. No exact definition of these is presented in this paper (see Mori and Kazama (2012) for details) (Fig. 21).

The numbers of completely destroyed and half destroyed houses are 48 and 133 in this site. Most of these destroyed houses belonged to the fill and boundary categories. It should be noted that no severely damaged houses were found at the center part of the fill embankment with maximum fill depth. Partially destroyed houses were distributed almost equally among the three categories. The partially destroyed houses on the cut area are mostly associated with the failure of roof tiles and cracks in the plaster, which may be attributed to the seismic motion. There were as many as 140 major ground cracks, most of which occurred at the boundary part near to the fill area.

In order to discuss quantitatively which type of ground displacement is most critical to house damages, the ratio of the number of damaged house per unit area on fill and boundary parts divided by the number of damages house per unit area on cut part was calculated, the result of which is shown in Table 3. Compared with the damaged houses on cut part, the normalized numbers of damaged houses on the fill and boundary parts are 26 and 25 with respect to the completely destroyed houses, and are 10 and 24 for half destroyed houses, respectively. The calculated results clearly show that the completely and half destroyed houses were predominantly in the fill and boundary parts. The calculated results for the partially destroyed houses show less predominance, with 3 in both parts.

Table 4 shows the main mechanisms (the modes of ground displacements) of completely and half destroyed

Table 4
Main mechanism of completely and half destroyed houses.

Disaster factor	Filled part		Boundary of filled and cut part		Cut part		Subtotal	Ratio (%)
	Comp.	Half	Comp.	Half	Comp.	Half		(Total houses: 181)
Ground crack	25	34	10	38	0	1	108	59.7
Differential settlement	3	29	2	22	0	0	56	30.9
Retaining wall failure	14	8	2	3	0	1	28	15.5
Fill slope failure	0	7	1	2	0	0	10	5.5
Seismic motion	1	3	1	3	0	3	11	6.1

Comp.: complete destroy, half: half destroy.
Selection of plural disaster factors is possible on one disaster housing site.

houses. Since duplicate counts on the mechanisms are permitted for each damaged house, the summation of the ratio exceeds 100%. In Table 4, the main mechanisms are classified into 5 types: ground cracks, differential settlement, retaining wall failure, slope failure, and seismic motion. In this terminology, slope failure refers to the slope failure at the end of the valley filled embankment, which is peculiar to this site; seismic motion refers to the damage to houses where no remarkable ground displacement was observed.

Ground cracks account for 60% of the failure mechanisms of severely (completely and half) destroyed houses. When the cracks passed through the ground beneath the foundation of a house, the house was severely damaged without exception. Differential settlement was the second most common cause, with a ratio of 31%. The degree of housing damages due to differential settlement was not so severe compared to those damaged by ground cracks. Most of the damage meant that the damaged homes fell into the category of half destroyed at most. The damage due to the failure of the retaining walls mainly for private residence accounted for 16%, with the damage due to this mechanism notably occurring in the fill area only. Damage due to slope failure amounted to 6%. The damage induced by seismic motion accounted for 6%, and it should be noted that this type of failure can occur everywhere, with less dependency on the area categories.

Summing up above findings on the Nankodai housing land with the branch-like valley filled embankments, the damages of houses mainly occurred on the fill and boundary categories, with 80% of the severely damaged houses associated with the ground displacement in the form of cracks and differential settlement. The damage due to seismic motion with no noticeable ground displacement was found to be very small.

These results may be influenced by the local features of the geotechnical conditions of Nankodai residential land. In order to obtain the common features of the main mechanisms leading to the damages of houses on the hillside embankments in Sendai city, further studies are necessary. It is, however, suggested that more attention should be paid to role that ground displacements plays, as the main mechanism leading to the severe damage of houses. This observation indicates that in planning countermeasures to the damaged hillside embankments, attention should be paid to improving the ground surface and the stability of geo-structures like retaining walls and slopes.

7. Classification of damages and actions for the reduction of damages

In this chapter we briefly discuss the classification of the failure type of hillside embankment during strong earthquakes and the current state of the actions in Japan toward the reduction of the damages.

7.1. Classification of damages of hillside embankment with an emphasis on the selection of countermeasures

In the past strong earthquakes in Japan and the 2011 earthquake, the hillside embankments for residential use have been damaged seriously. The failures may be roughly classified into the following 4 types: (1) landslides in the soft original ground, (2) landslide type failure along the boundary between fill and original ground, and (3) ground displacements due to shallow slips, and 4) ground displacement without slippage due to seismic motion. In types (3) and (4), the apparent modes of ground displacement at the surface include cracks, differential settlements, steps in the ground, failure of retaining walls, and slope failures.

This classification may not be complete but is nevertheless a good guideline for the selection of countermeasures for damaged hillside embankments. As a countermeasure to class (1) landslide in the soft original ground, the improvement of the original ground is recommended. For the class (2) landslide type failure along the boundary between fill and original ground, restraining piles and groundwater drainage are recommended. For class (3) ground displacements due to shallow slips, soil improvements and groundwater drainage works are recommended. For the class (4) ground displacements without slips, reinforced embankment and soil improvements are recommended. The above discussions may be summarized as shown in Table 5.

It should be noted that countermeasures for the new construction of residential land are different from those

Table 5
Tentative classification of failure types and countermeasures.

Class	Failure type	Common features	Geotechnical causes	Countermeasure
(1)	Landslide in soft original ground	Main scrap at the top Upheaval at the toe	Weak original ground	Ground improvement of original ground
(2)	Landslide type failure along boundary between fill and original ground	Main scrap at the top Upheaval at the toe	Weak boundary between fill and original ground Shallow water level	Restraining pile Groundwater drainage works
(3)	Ground displacements due to shallow slips	Shallow slip failure Open cracks Steps in the ground Differential settlement Slip failure at the tip of embankment	Weak fill materials Shallow water level Loose soils	Groundwater drainage works Soil improvements
(4)	Ground displacements without slips	Open cracks Steps in the ground Differential settlement Settlement due to densification Failure of retaining walls	Weak fill materials Shallow water level Liquefaction of sandy soil	Soil improvements Reinforced soil

applied to the damaged existing land, since the countermeasures against possible failure in the residential land prior to construction can be more flexible in the planning.

The failure type of the landslide in the original ground, class (1), was not extensive during the 2011 earthquake because most of the basement rock of developed housing area in Sendai city consists of tuffaceous sand stone or tuffaceous mudstone in the age in the Pleistocene. In one site (Ootoya-machi no. 4 in Table 1), the surface of the original ground was humus soil with low SPT N values, and the humus soil is deposited on the soft rock (Dainenji-layer). This site could be classified into type (1). In Table 1, Ootoya-machi was however classified into classes (2) and (3). Class (1) failures in the past earthquakes were observed in the 1993 Kushiro-oki earthquake (Yanagisawa et al., 1994). Landslide type failures along the boundary, class (2) type failures, were observed during the 1995 Great Hanshin Earthquake, the 2004 Chuetsu earthquake, the 2007 Chuetsu-Oki earthquake, and the 2011 earthquake. Midorigaoka 3 choume and Oriate 5 choume in the 2011 earthquake can be classified into this class; however, even in these cases, the housing lots were observed to be damaged more severely by ground displacements with shallow slips, which are class (3) type failures. In the case of Nankodai, the damage to residential land may be classified as ground displacement without slippage, the class 4 type failure), which is the consequence of strong seismic motion. It should be noted that the liquefaction induced failure of sandy soils can be classified as a class (4) type failure. This can be justified by the following two reasons: (1) the liquefaction induced flow of fill embankment is not associated with clear slippage, and (2) the countermeasures to liquefaction induced flow mainly involve soil improvements. Liquefaction induced failure of fill embankment were noted in the past earthquakes, e.g., in the 1995 Great Hanshin Earthquake (see Okimura et al. (1999a) among others). In the 2011 earthquake, the effects of liquefaction can be observed at Midorigaoka 3choume (no. 2 in Table 1), Keiwa-machi (no. 5), and Jingahara (no. 18).

7.2. Action of Japan for the reduction in the seismic damages of residential land

We here briefly review the actions in Japan toward the reduction of severe damage to residential land during strong earthquakes. More information about the regulations and the act toward the reduction of damages can be found in the JGS proposals (2011).

In 1962 a ‘‘Law on Regulation of Residential Land Development’’ was put into force in response to the damage done to residential land due to heavy rainfall. In 2007, a new standard was set up to respond to the widespread damage to housings during strong earthquakes and the ‘‘Act of Promotion of Earthquake Resistant Residential Land’’ was put into effect. In this act, ‘‘Developed Residential Land Disaster Prevention Areas’’ were newly set up in order to extend high performance to residential land in strong earthquakes. This is in addition to the ‘‘Regulated Area of Residential Land Development’’ in the ‘‘Law on Regulation of Residential Land Development’’, which applies to only 2.7% of national land in Japan.

For the specification of the developed residential land disaster prevention areas, several steps should be followed. The completion of this act requires the resident must bear part of the expense; and the cooperation of the resident is essential. As a first step, the importance of the promotion of the earthquake resistant residential land should be understood by the resident.

In the act to promote earthquake resistant residential land, addressing the possibility to landslide type failure along the boundary between fill and the original ground is considered most crucial. However, this failure type may not occur in cases where the fill materials are rather poor and the water table is shallow.

As has been mentioned previously, the collapse of housing due to the ground displacement was the predominant mechanism in many cases in the 2011 earthquake. Engineering work in the form of countermeasures is expected to be effective against the failure mechanisms expected to occur in future earthquakes. The guidelines for these, including the damage due to ground displacement with shallow slippage are now being prepared in the committee of the Ministry of Land, Infrastructure, Transport, and Tourism.

8. Conclusions

The 2011 off the Pacific Coast of Tohoku Earthquake resulted in severe damage to hillside embankments for residential use in the Iwate, Miyagi and Fukushima prefectures. Particularly, the damage in Sendai city was widespread, with more than 7000 houses damaged. The causes of the damages of hillside embankments and the relationship between the patterns of the ground displacements and the degree of the damages of housings were discussed in this paper. A fundamental classification system for the failure types of hillside embankments is proposed, which provides a good guideline for the selection of countermeasures to damaged residential land. The main conclusions from this study may be summarized as follows:

(1) Most of the damage to housing may be attributed to the ground displacement of the softly filled soils of the hillside embankment. Few houses were damaged due to seismic motion without ground displacement and the degree of the damage in these cases was not severe.
(2) The fill materials of severely damaged hillside embankments were composed of soils containing a high ratio of fine particles, which may result from poor compaction during construction work, the rising of water tables, and the degradation to hillside embankments with elapsed time.
(3) The landslide type failure along the boundary between fill and original ground was limited and ground displacement due to shallow slippage and due to strong earthquake motions were devastating to housing damages.
(4) The residential land which had been seriously damaged during the 1978 Off Miyagi Prefecture Earthquake and where countermeasures had been taken were again damaged during the 2011 off the Pacific Coast of Tohoku Earthquake. A comparison of the damages in the two earthquakes indicates that the countermeasures set up after the 1978 earthquake were effective in preventing landslide type failure; however, they were not effective in reducing housing damage.
(5) The countermeasures taken in damaged residential land after the earthquake should be compatible with the causes of the damage done to housing, which implies that ground displacements must be minimized as much as possible. The hillside embankment failures were classified into 4 types of failure (Table 5), which provides be a good guideline for the selection of countermeasures to be taken in damaged hillside embankments.
(6) It is strongly recommended that countermeasures are put into place prior to a strong earthquake in residential hillside embankments with soft fill materials. This will reduce the risk of seismic damages and will benefit residents in many ways. The understanding of the resident with regard to the necessity of creating earthquake resistant residential land is of urgent importance.

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